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Ultrasonic Cave Mapping

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Surveying the internal structure of a cave is an important part of any archaeological or palaeontological investigation of a cave locality. However, the use of standard topographical surveying techniques is often difficult due both to the irregular nature of the structure and to the difficult working conditions. This study uses a novel method based on ultrasound reflections to produce an accurate 3D model of Kitley Shelter Cave, an archaeological cave in Yealmpton, Devon. This model enables the cave system to be visualized leading to a better understanding of the site and its taphonomy.

Keywords: CAVE ARCHAEOLOGY, SURVEYING, ULTRASOUND SCANNING, 3D-COMPUTER IMAGING.

Introduction

Cave surveying techniques

Caves are generally either surveyed in a topological fashion recording the bearing, inclination and length of the passages or more exhaustively using standard interior surveying techniques to record the positions of the walls of the passages (Worthington, 1987; Ellis, 1988). Neither of these options is ideal for use in palaeontological research (Hunt *et al.*, 1987; Grady, 1994). The first option does not allow a comprehensive visual impression of the cave to be recorded, while the latter approach is time-consuming and may encounter difficulties due to access problems and the prevalence of ill-defined, curved surfaces which are difficult to specify precisely without fixing a number of artificial marker points to surfaces. However, with time and care these difficulties can be overcome and there are excellent surveys of archaeological caves, for example, the survey of Kent's Cavern in Devon (Proctor & Smart, 1989).

The automated scanning system described in this paper can get around many of these problems. It is reasonably quick and it produces profiles of the passageway at known distances into the cave system. This approach allows a full and accurate 3D reconstruction for later visualization.

There are a number of computer packages to help cave surveying. These are mainly designed for topological surveys and help with loop closure and error distribution. Some also have 3D visualization features, although these are generally for displaying survey line data rather than passage reconstructions based on sections (for a review see Wookey, 1994).

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Ultrasound scanning

A number of options are available for automatically calculating the distance of an object from a point (Gibson, 1996). The most accurate systems use electromagnetic radiation (either radar or laser sources). Laser sources are highly dependent on the precise reflective properties of the target object and are unsuitable when used on rough, bare rock surfaces. Radar is considerably better, but suitable equipment is neither cheap nor easily portable. Sound waves are a suitable alternative for range finding where exact precision is not required (Gibson, 1991*a*). Ultrasound transducers are relatively inexpensive, and usually ultrasound beams reflect well off rock surfaces. The lack of precision is due to the difficulty in obtaining a narrow ultrasound beam and the problem of shaping a precisely defined sound pulse.

Survey Site

The Kitley caves are located in Devonian limestone at Western Torrs Quarry in Yealmpton, South Devon (National Grid Reference SX 57505125). The quarry,

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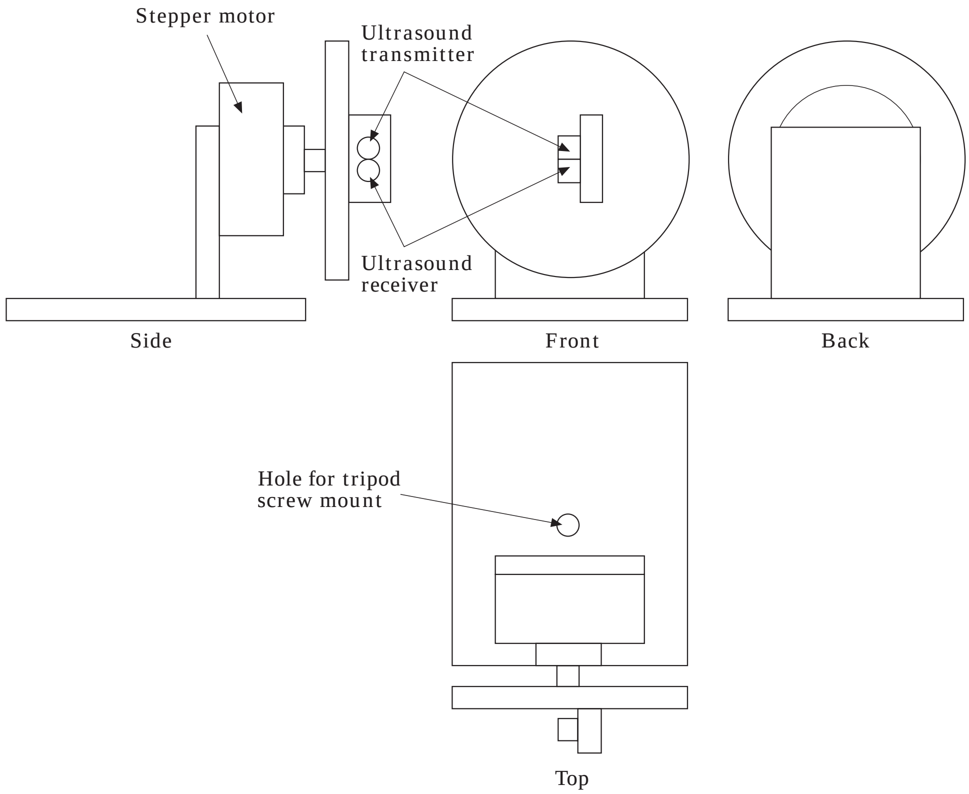

Figure 1. The design of the scanning head. An ultrasound transmitter and receiver are mounted on the spindle of a stepper motor. This allows a pulse of ultrasound to be directed radially and the echo signal recorded at 7·5° intervals.

now abandoned, is located in the side of a natural limestone bluff which overlooks a narrow steep-sided valley formed by the river Yealm. An extensive cave system, the Kitley Show Caves, is open to the public but many more caves and fissures penetrate the limestone on both sides of the river Yealm, including the Kitley Shelter Cave which is the subject of the present study.

Kitley Shelter Cave is located at a high level within the limestone outcrop, and prior to archaeological excavation the cave was partially filled with cave breccias, flowstones and unconsolidated cave sediments. Since 1994 an archaeological research project, led by the University of Sheffield and the University of Wales Lampeter, has investigated the archaeological and palaeontological remains in Shelter Cave. During the research excavations the locations of archaeological finds and faunal remains have been recorded using local reference datums consisting of bolts drilled into the cave roof. It was realized that an accurate survey of the accessible part of the cave was desirable in order to gain a visual impression of the cave and to determine the spatial relationships between finds in different parts of the cave system.

Materials and Methods

The basic approach used for the survey system is a rotating ultrasound emitter mounted so that the beam scans the walls of the cave in a vertical plane. The system is able to calculate the distance of the wall from the emitter at any point in this sweep and so is able to calculate the profile of the cave in the scanning plane. By moving the emitter through the cave system a set of profiles is built up as a stack of slices. These slices can then be reassembled in a CAD program to reconstruct the 3D shape of the cave system.

Schematic diagram of the system

The ultrasonic scanner consists of an ultrasound emitter and receiver mounted on the spindle of a stepper motor. The stepper motor and the ultrasound transmitter are controlled via a laptop computer which also reads the signal picked up by the ultrasound receiver. The emitter sends out a pulse of ultrasound and the echo is picked up by the receiver. The time taken for the echo to arrive depends on the distance from the transmitter to a solid object such as the wall of the cave. The stepper motor then rotates the transmitter and receiver through 7·5° and the process is repeated. A complete circular scan is built up in very much the same way as radar with the computer storing the ultrasound echo at each of the 48 scan orientations and then plotting them on the screen as a radial map. Figure 1 shows a diagram of the mechanical aspects of the system. Figure 2 shows a schematic of the

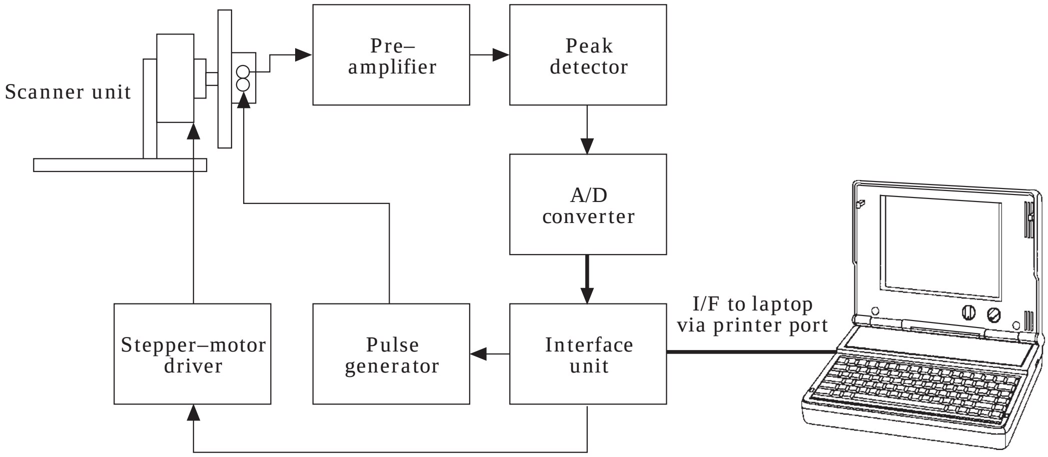

Figure 2. Schematic diagram of the data capture system. The computer program controls the position of the stepper motor and sends out ultrasound pulses in known directions. The echo signal is recorded for each ultrasonic pulse and used to build up an image of the cave walls.

electronics. Full plans, including printed circuit board designs, can be obtained from the authors.

Description of the process

The scanner produces a radial scan perpendicular to the axis of the stepper motor. To produce an accurate 3D reconstruction both the position and orientation of the axis needs to be known. To map a cave system, a zero point at the entrance is first defined using standard surveying techniques. Then a series of secondary markers are set up at convenient places within the cave and surveyed by measuring their distance, bearing and inclination from each other and from the zero point as convenient.

The scanner unit is then moved through the cave. It is set up at convenient points at approximately 0·5 m intervals and the bearing and inclination of the spindle recorded. In this particular case, the spindle was always held horizontal, though there is no particular requirement to do this. The position of the spindle was defined by the distance, bearing and inclination from one of the previously surveyed markers.

Once the 6 degrees of freedom of the centre of the scan have been defined, the scanning process is automatic and takes about a minute. The actual time taken to complete a single scan depends on the number of echo traces taken for each segment (repeated echoes are software integrated to improve the signal to noise ratio). The scan can be displayed immediately on the computer screen allowing visual confirmation that a useful image has been obtained.

The resolution of the system is independent of the distance to the reflecting surface and is currently approximately a distance of 5 cm with an angular resolution of 10° (see Figures 3, 4 and 5). The latter value is constrained by the beam width of the ultrasound transducer and the former value by the difficulties in precisely defining the edge of the pulse. Reducing the transmitter beam width will reduce both these values as would improved software. There are, however, constraints on size and portability of the equipment that mean that a realistic limit to the precision of this approach would be an arc of 1° and a distance of 1 cm. The maximum measurable distance depends on the ambient noise level and the sound reflection properties of the cave, but preliminary tests showed that the prototype could identify echoes from walls more than 10 m away in ideal conditions.

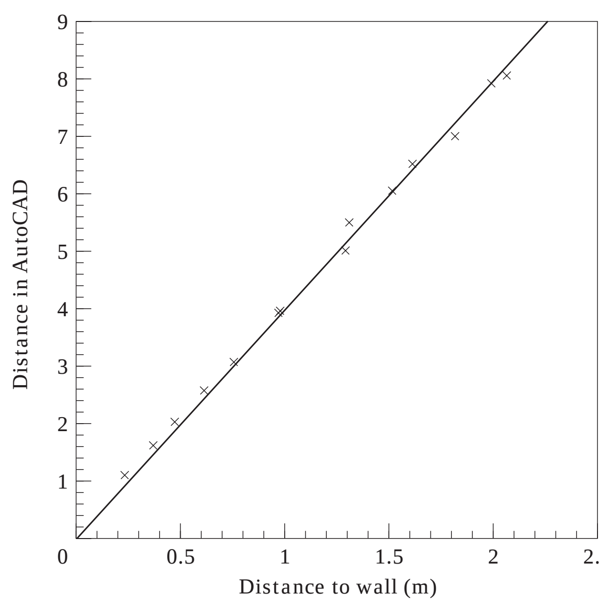

Figure 3. The relationship between scans of known distances and the distances in arbitrary AutoCAD units after tracing. The equation of the best fit straight line through the points is $y = 4{\cdot}020 \times$ with $r^2 = 0{\cdot}9976$. This relationship was then used to calibrate subsequent measurements.

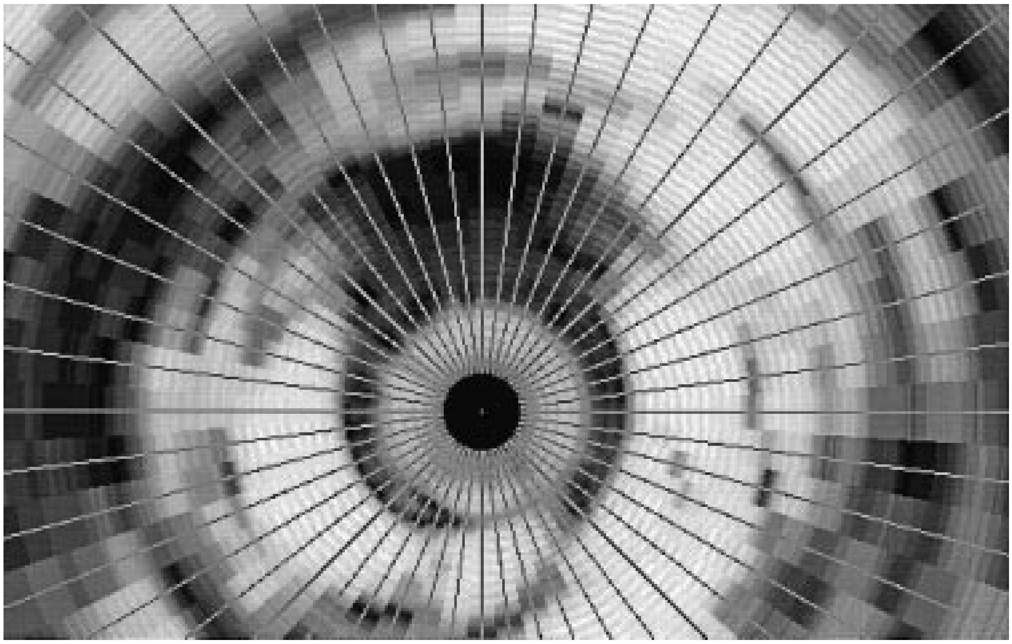

Figure 4. The raw output from the scanner program. The diagram should be interpreted in very much the same way as a radar. The distance from the centre represents the echo time, and the brightness of the shading represents the strength of the reflected signal. The superimposed 48 point star indicates the centre of the beam.

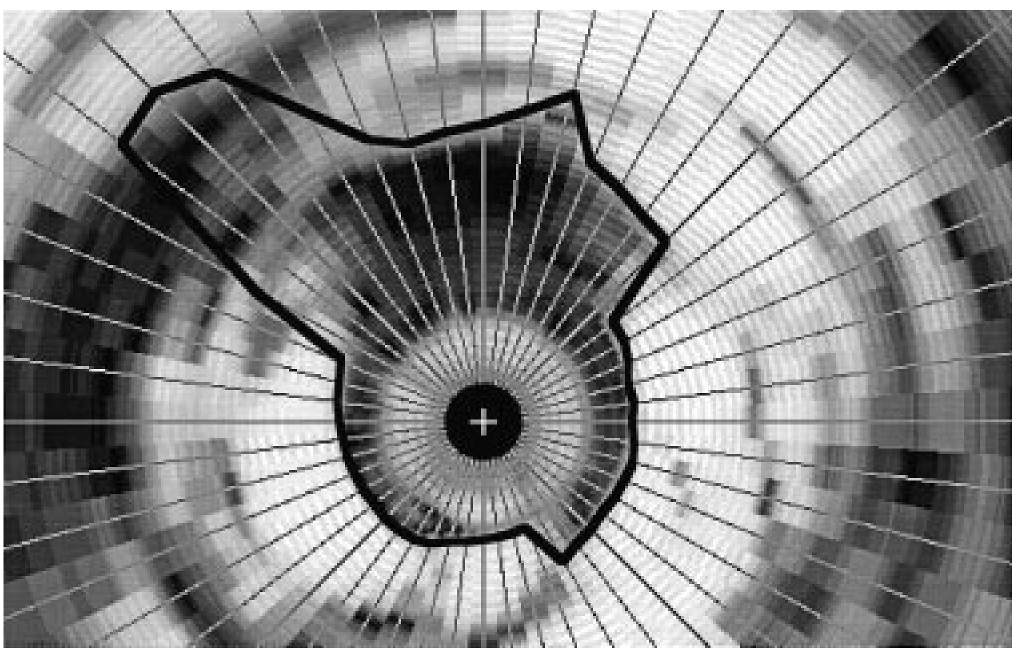

Figure 5. The raw output overlaid with a trace representing the estimated position of the wall of the cave. This is generally the first large reflection signal.

Data processing/software

The software can be divided into two parts: data capture and data analysis. The data capture software is responsible for controlling the scanner and storing the ultrasound echo data. Echo digitization occurs in real time, so parts of the software had to be written in machine code to maximize the data throughput. This results in the digitization speed being dependent on the actual running speed of the host computer and therefore the device needs to be calibrated by recording several scans at known distances from a solid object. In this case, this was done by arranging the scanner at known distances from the wall of a building. Figure 3 shows the results of this calibration exercise.

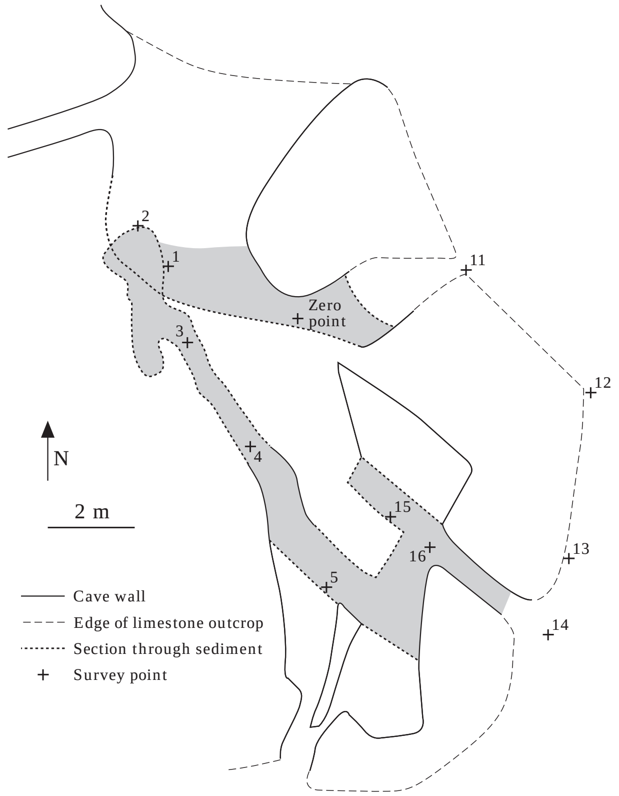

Figure 6. Plan of Kitley Shelter Cave obtained by traditional surveying means. Stipple indicates the parts of the cave surveyed with the ultrasound scanner.

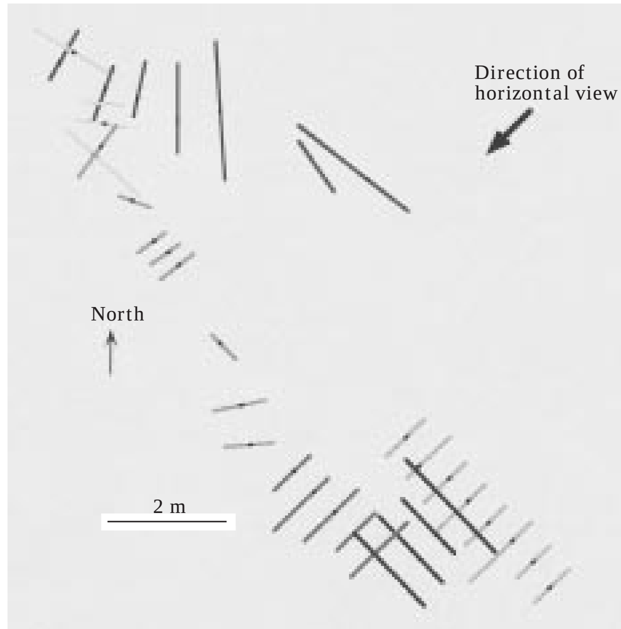

Figure 7. Plan view of the set of vertical profiles correctly scaled and orientated in AutoCAD. The arrow shows the direction of the horizontal view in Figures 8 and 9.

The data analysis stage takes the raw data files from the data capture program and ultimately produces an accurate 3D CAD model of the cave. This is presently a fairly time consuming process, but there is potential for several of the stages to be automated.

Firstly, the radial scans are converted into a standard rectangular coordinate based TIFF picture file. This is then read into the graphics package Canvas (Canvas, 1993) which handles both bitmap and object based drawing. The central point is then marked and the outline of the cave is drawn by hand as an overlay. A set of 48 radical lines are used as a drawing aid. These hand drawn vectors are then saved as a DXF (data exchange format) file that can be read by AutoCAD (AutoCAD, 1996).

In AutoCAD, the vector outline is scaled using the factor calculated from the calibration experiments and then rotated and translated so that the position and orientation of the axis of the scan matches that recorded from the cave. Each separate scan outline is converted to its original cave coordinates and can be imported into a single 3D AutoCAD file.

The outlines can then be used as surface boundaries which are spanned by surfaces to ‘‘skin’’ the wire-frame structure, producing a 3D surface model of the cave.

Results

Plan of cave

Figure 6 shows the plan of Kitley Shelter Cave obtained using standard surveying techniques. The section of the cave surveyed by ultrasound scanning is indicated.

Sample cross-section scan

Figures 4 and 5 show how the cross-sectional profile is built up. Figure 4 shows the raw data from the scanner, superimposed onto a 48 point star so that the beam centre can be clearly identified for each of the scans. Figure 5 shows how the cave walls are identified on this ‘‘radar’’ picture and drawn on as an overlay. Note, on Figure 5, the wall at the 10 o’clock position is poorly defined, and there is some interpretation ‘‘by eye’’.

Assembled traces

Each profile is recorded along with the surveyed position and direction of the stepper motor axis. This defines the position of the centre of the scan and the orientation. The scale information is obtained from the calibration curve. This information is used to shift, scale and orientate the profiles in AutoCAD. Figures 7 and 8 show the correctly orientated scans. Once the profiles are orientated, the wire frame model can be converted into a surface model, a process known as ‘‘skinning’’. This produces a realistic looking 3D

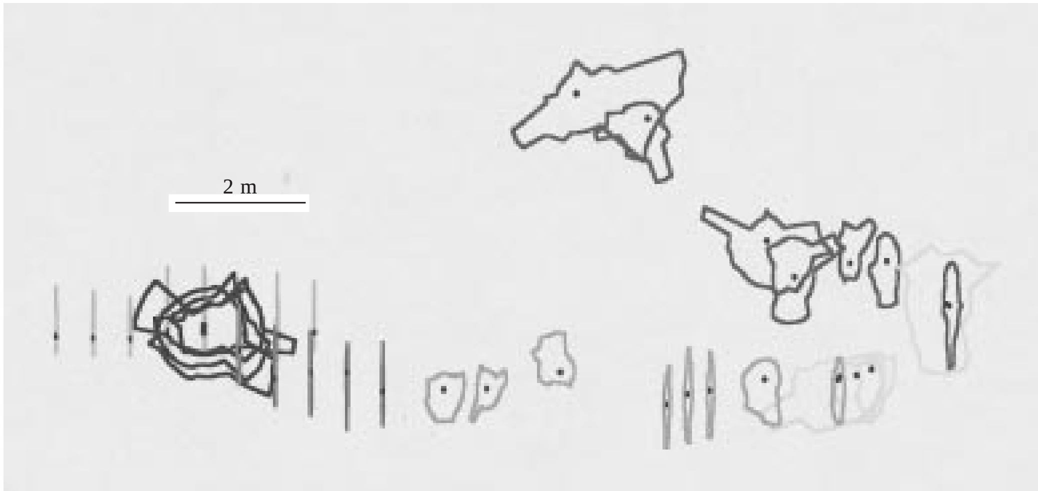

Figure 8. This figure shows an elevation of the profiles viewed from the direction indicated by the arrow in Figure 7. The change in altitude at different locations within the cave is apparent.

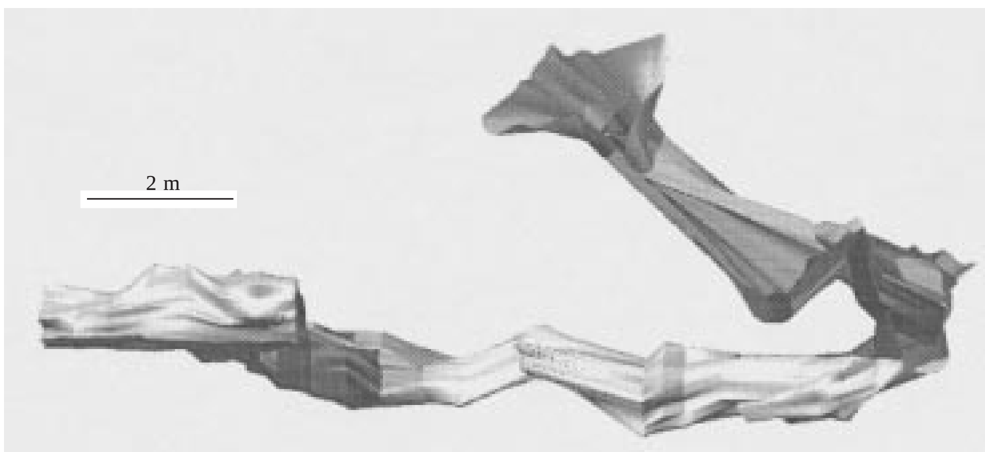

Figure 9. Fully rendered 3D representation of Kitley Shelter Cavae obtained by ''skinning'' the vertical profiles. Direction of view as in Figure 8.

rendered model of the cave system that can be viewed from any particular orientation (Figure 9), and with the right software, can even be walked through.

Discussion

As mentioned before, accurate surveying is a vital part of archaeological and palaeontological recording. The ultrasound scanning technique presented here allows accurate surveying and visualization to be performed in restricted spaces relatively quickly.

The visual display of the surface of the cave system (Figure 9) is a useful aid in the interpretation of the geomorphological and taphonomic processes that may have influenced the movement and deposition of sediments, fauna and artefacts within the cave. The 3D model provides information about the directions and gradients of the segments of cave passage, the maximum volumes of sediments that can be contained within the cave, and the locations of points of constriction where movements of large clasts may have been obstructed. Given appropriate fluid dynamic modelling software, the 3D model could also be used to simulate sediment flow within the cave. In addition, at Kitley Shelter Cave the locations of finds and sections through the cave sediments were recorded by measuring their coordinates along three orthogonal axes relative to datum points fixed to the roof of the cave. These locational data can be incorporated easily into the AutoCAD model of the cave to allow the display of the position of the finds within the cave system.

The surface of the cave wall could have been recorded in a similar fashion to the individual finds (i.e. manually, using measurements from datum points in the x-, y- and z-dimensions). However, this would have been extremely time consuming as it would have required 144 measurements (x-, y- and z-displacements for each of the 48 radial positions) for each profile of the cave wall recorded to achieve the same density of information as the ultrasound scan. The time required for basic data processing and manipulation is considerably higher for the scanning method, although there would be no difference if the traditional survey had the same amount of information as the ultrasound one.

The use of ultrasound in caves will disturb bats. The 40 kHz transmitter used is very close to the echo-locating signal of brown long-eared, Daubenton's, whiskered, Brandt's and pipistrelle bats (genera *Plecotus*, *Myotis* and *Pipistrellus*). However, any human activity in a cave will disturb bats and cave surveying in general should not be undertaken during sensitive times of the year such as the hibernation period (K. Jones, Roehampton Institute pers. comm.).

There are two areas where improvements could be made in the prototype scanning system. Firstly, the main cause of inaccuracy in ultrasonic surveying is due to the width of the ultrasound beam. This can be ameliorated by either using a narrower beam (Gibson, 1991*b*), or by using an array of receivers rather than just a single one so that different parts of the beam can be resolved. This requires considerably more sophisticated equipment, but is in principle achievable by increasing the cost of the unit and by improving the data capture hardware and software (Altes, 1995). Similarly, using wideband sonar techniques can also allow improved spatial resolution (Wehner, 1987). The second area for improvement is the reconstruction software. Currently, much of the processing of the scan images needs to be done by hand and could be automated using image recognition style algorithms. Image recognition is notoriously unreliable, but the problem in this case is quite well circumscribed and the position of the first large echo could be automatically detected to automate the identification of the position of the reflecting surface.

In conclusion, the results obtained from this relatively cheap system are very encouraging as they provide accurate 3D models of the complex geometry of a cave system in a comparatively short space of time.

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References

Altes, R. A. (1995). Signal processing for target recognition in biosonar. *Neural Networks* **8,** 1275–1295.

AutoCAD (1996). Version 13. San Rafael, California: AutoDesk Inc.

Canvas (1993). Version 3.5. Miami, Florida: Deneba Software.

Ellis, B. (1988). An introduction to cave surveying. *BCRA Cave Studies Series No. 2*. London: BCRA.

Gibson, D. (1991*a*). Accuracy problems in ultrasonic and light-beam rangefinders. *Journal of the BCRA Cave Radio and Electronics Group* **6,** 9.

Gibson, D. (1991*b*). Improving directivity in ultrasonic rangefinders. *Journal of the BCRA Cave Radio and Electronics Group* **6,** 9–10.

Gibson, D. (1996). Electronics in surveying. *Journal of the BCRA Cave Radio and Electronics Group* **23,** 25–26.

Grady, F. (1994). Collecting in caves. In (P. Leiggi & P. May, Eds) *Vertebrate Palaeontological Techniques, Volume 1*. Cambridge: Cambridge University Press, pp. 77–81.

Hunt, C. O., Brooks, I. P., Coles, G. M. & Jenkinson, R. D. S. (1987). Archaeological surveying in caves. *Cave Science—Transactions British Cave Research Association* **14,** 83–84.

Proctor, C. & Smart, P. (1989). A new survey of Kent's Cavern, Devon. *Proceedings of the University of Bristol Speleological Society* **18,** 422–428.

Wehner, D. R. (1987). *High Resolution Radar*. Norwood: Artech.

Wookey (1994). *Survey Software*. Compass Points, BCRA. Issue 3. http://www.chaos.org.uk/survex/cp/CP03/CPoint03.htm

Worthington, S. (1987). Review of cave surveying techniques. *Cave Science—Transactions British Cave Research Association* **14,** 56–59.